

# Integrating tracking in concentrating photovoltaics using non-rotational symmetric laterally moving optics

Fabian Duerr<sup>a</sup>, Pablo Benítez<sup>b,c</sup>, Juan Carlos Miñano<sup>b,c</sup>, Youri Meuret<sup>a</sup> and Hugo Thienpont<sup>a</sup>

<sup>a</sup>Vrije Universiteit Brussel, Faculty of Engineering Sciences, Brussels Photonics Team

B-PHOT, TONA-FirW, Pleinlaan 2, 1050 Brussels, Belgium

<sup>b</sup>CeDInt, Universidad Politécnica de Madrid (UPM), Campus de Montegancedo, 28223

Pozuelo de Alarcón, Spain

<sup>c</sup> Light Prescriptions Innovators, 16662 Hale Ave., Irvine, CA USA 92606

## ABSTRACT

In this work the concept of integrating tracking in concentrating photovoltaics is briefly summarized and possible fields of application are classified. A previously proposed system setup relies on the use of two rotational symmetric laterally moving plano-convex lenses to achieve  $500\times$  concentration over an angular range of  $\pm 24^\circ$ . However, the circular lens apertures are less suitable for application in lens array structures. A new design algorithm based on the Simultaneous Multiple Surface algorithm in three dimensions (SMS3D) demonstrates the ability to address this problem. Performance simulations show that the resulting non-rotational symmetric design outperforms its conventional rotational symmetric counterpart.

**Keywords:** Solar concentrators, Tracking integration, Nonimaging Optics, Lens system design, Beam Steering

## 1. INTRODUCTION

Concentrating photovoltaic (CPV) systems employ optics to concentrate direct sunlight onto solar cells. The ratio of input and output aperture areas defines the concentration ratio of the concentrating system. The significant decrease of the required solar cell area provides a pathway to lower cost, as expensive semiconductor material is replaced with inexpensive mirrors or lenses. Furthermore, high-efficiency multi-junction solar cells can be used to boost the conversion efficiency of CPV modules.<sup>1</sup> The angular acceptance of the optics and the achieved level of concentration are two measures that specify the overall performance of the optical design. The angular acceptance determines the maximum incident angle for which the light rays entering the optics still reach the solar cell. The second law of thermodynamics determines the maximum theoretical concentration limit for a given angular acceptance of the optics.<sup>2</sup> Available CPV systems vary widely according to the desired concentration ratio, the kind of used optics (reflective and/or refractive) and the type of deployed solar cells. A possible concept to classify these different systems is the concentration ratio. High-concentrating photovoltaics (HCPV) typically perform at concentration ratios beyond  $400\times$  and make use of multi-junction solar cells. This level of concentration normally demands an accurate dual-axis tracking of the sun's diurnal and seasonal movement. Medium-concentrating photovoltaics (MCPV) with typical concentration ratios around  $10\times$  to  $20\times$  are installed on single- or dual-axis trackers using silicon or other solar cells. Low-concentrating photovoltaics (LCPV) with concentration ratios around  $2\times$  to  $4\times$ , typically enhance conventional silicon solar panels and may be installed on a tracker.<sup>3</sup>

Despite the vast number of these differing concepts, almost all have something essential in common: concentrating optics plus deployed solar cells are treated as an inseparable static unit which is then - usually within an array - packaged as a concentrating photovoltaics module. This module can then be installed on an external solar tracker. In contrast with this clear separation between (stationary) CPV modules and external solar trackers, the here discussed concept of a tracking-integrated concentrating photovoltaic system is to transfer part of this external solar tracking functionality to within the concentrating photovoltaic module. To gain a tracking-integrated functionality, additional degrees of freedom are needed on the module level. This can be achieved

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Further author information: (Send correspondence to Fabian Duerr)  
Fabian Duerr: E-mail: fduerr@b-phot.org, Telephone: +32 (0)2 629 10 19

by internal relative movements or non-moving approaches such as liquid crystals. This inherent difference is exemplary illustrated in Figure 1 for relative moving lens arrays as discussed in this work.

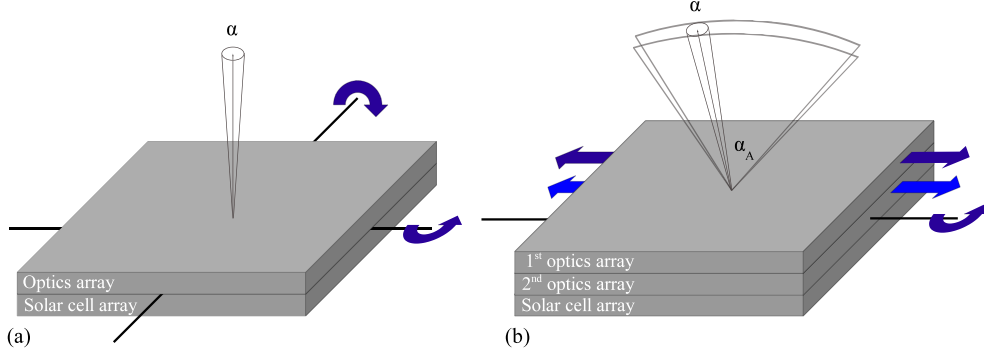


Figure 1. Inherent difference between a conventional (stationary) CPV module with its acceptance angle  $\alpha$  (a) and a tracking-integrated CPV module with the aperture angle  $\alpha_A$  of the optical system and the acceptance angle  $\alpha$  for a particular incident direction (b).

For conventional CPV modules, the acceptance angle  $\alpha$  of the deployed optics is a single measure which determines the demands and tolerances that apply to the used external solar tracker. In case of a tracking-integrated CPV module, two parameters are necessary for a full description. The aperture angle  $\alpha_A$  of the module and the acceptance angle  $\alpha$  of the deployed optics. The aperture angle of the module defines the angular range that can be covered by the integrated-tracking and therefore determines the demands for an additional external solar tracker, if needed. The acceptance angle then determines the angular tolerances for each particular direction within the aperture angle of the optical system.

Even though a tracking-integrated CPV module might lack an ideal concentration performance over the entire aperture angle of the optical system, this shortcoming is compensated by a strong reduction of the external solar tracking effort, possibly resulting in a lower overall cost. Furthermore, external tracking constructions can be optimized with respect to size, stability and material consumption.<sup>4</sup> This is especially important regarding possible roof top installations. On the other hand, additional degrees of freedom, such as internal movements raise the complexity of the CPV module and more optics arrays will reduce the optical efficiency on a system level. A detailed benefit-cost analysis will be necessary to identify those tracking-integrated CPV systems that show great promise for all demands.

One objective of this work is to establish the general concept of tracking integration in CPV, show its wide range of possible applications and emphasize its capabilities. For this reason, possible applications and specific system configurations are briefly discussed in Section 2. In previous work a system setup which makes use of rotational symmetric laterally moving lenses was proposed.<sup>5</sup> However, when targeting lens array structures this approach has certain shortcomings which are discussed in Section 3. An extended design algorithm based on the SMS3D design algorithm<sup>6</sup> is presented in Section 4 which enables a symmetry matching between the desired field of view and the designed optics. First ray tracing results demonstrate its superiority compared with its conventional rotational symmetric counterpart. Finally, in Section 5, conclusions are drawn and an outlook is given.

## 2. POSSIBLE APPLICATIONS OF TRACKING INTEGRATION IN CPV

The concept of tracking integration in CPV is gaining momentum. Different system configurations following this approach were already discussed in the literature. It is possible to distinguish between two specific application types.

1. Exploit the additional aperture angle due to tracking integration in order to reduce the external tracking effort (see, for example<sup>7-9</sup>)
2. Apply integrated solar tracking to fine-tune the total tracking functionality allowing coarse external solar tracking (see, for example<sup>10</sup>)

Furthermore, it is of course possible to combine both functionalities in order to reduce the external tracking effort and to allow coarse remaining external solar tracking at the same time. A clear drawback of reducing the external tracking is the reduced yearly insolation due to off-axis cosine losses, especially if no external tracking is used. However, the comparison of the potential annual energy yield for different single axis tracker with dual axis tracker installations shows moderate differences, e.g. for miscellaneous places in Europe.<sup>11</sup> It is obvious that the application of dual axis trackers in HCPV mainly arises from the theoretical point concentration limit for single axis trackers than a maximized insolation - it is rather an appreciated necessity.

Therefore, this tracking-integrated approach can be very useful to further increase the point concentration ratio and make HCPV available for single axis tracker installations. Changing the possible alignment of a single axis tracker can reduce the necessary aperture angle  $\alpha_A$  of the CPV module and thus the demands on the tracking integration. The aperture angle is minimal for a polar aligned single axis tracker installed towards the South. In this particular configuration, the tilt angle is equal to the latitude of the installation and the rotational axis of the single axis tracker equals the earth's axis of rotation. The aperture angle of the system then reduces to approximately  $\pm 24^\circ$  (axial tilt of the earth) in North-South direction and the sun's half divergence angle in East-West direction which is shown in Figure 2(a). For deviations from the polar aligned rotational axis in North-South direction, the angular range becomes asymmetric regarding the origin and the necessary aperture angle for tracking integration increases. The angular range for a horizontally aligned single axis tracker for latitude of  $30^\circ$  (Seville, Spain) is shown in Figure 2(b).

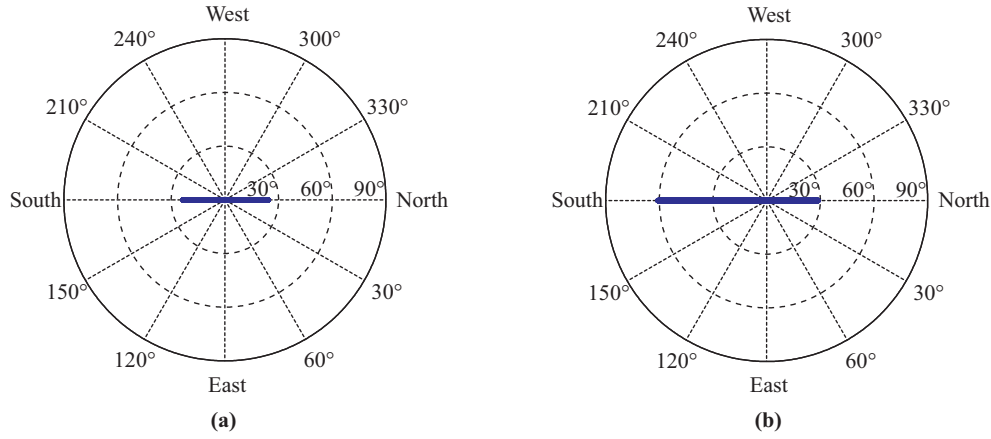


Figure 2. Angular range of incident sun light for CPV modules mounted on a single axis tracker that is (a) polar aligned or (b) horizontally aligned (Both for Seville, Spain)

Within the upcoming sections, the tracking integration for point concentration systems on a polar aligned single axis tracker using laterally moving lenses will be investigated and discussed. This specific configuration is defined by the aperture angle  $\alpha_A = \pm 24^\circ$  and the acceptance angle  $\alpha = \pm 0.28^\circ$  (divergence angle of sun light). Particular attention will be given to its suitability for lens array structures.

### 3. LATERALLY MOVING ROTATIONAL SYMMETRIC LENSES

As mentioned in the introduction, the optical design of rotational symmetric laterally moving lenses based on an extended SMS2D algorithm and its use for tracking integration on a single axis polar tracker were already proposed.<sup>5</sup> As a final result it was possible to design a system achieving about  $500\times$  point concentration over the entire angular range and for the sun's half divergence angle of  $\pm 0.28^\circ$ .

However, circular lens apertures are not fully suitable for application in lens array structures. Keeping these circular apertures result in inevitable spaces between them and will thus reduce the output per square meter. Therefore, rectangular lens apertures are normally preferred. The evaluation of the concentration performance over the entire angular range is repeated again, this time for squared lens apertures as well. The two systems shown in Figure 3 are identical except their different aperture shapes.

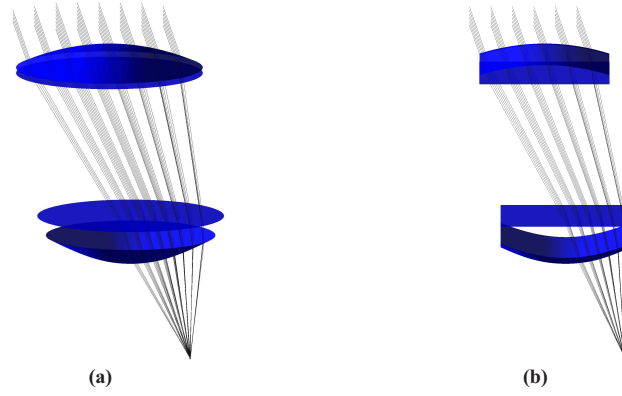


Figure 3. Shown are identical laterally moving lenses setups except for their circular (a) and squared (b) entrance apertures shapes

The analysis of these systems is done analogously to the previous work. The point concentration ratio of both systems is investigated for monochromatic light, a half aperture angle of  $24^\circ$  and an angular acceptance of  $\pm 0.28^\circ$ . All ray tracing simulations in this work are done using the MATLAB-based ray tracer OPS\*. A simple iterative method within the ray tracer makes sure that the second lens is always properly shifted for any incident direction. The optimal receiver position is then obtained by the ray tracer. An analysis of the mapping of these positions shows a law close to  $r \propto \tan(\theta)$ . In both cases, the actual receiver size is defined in such a way that 95% of the energy entering the first lens aperture is collected at the receiver. For the circular entrance aperture a circular receiver, whereas for the squared entrance aperture a squared receiver (matching typical solar cells' aspect ratio) are used. Figure 4 shows the concentration ratio against the incident angle for circular (upper curve) and for squared (lower curve) entrance apertures, respectively.

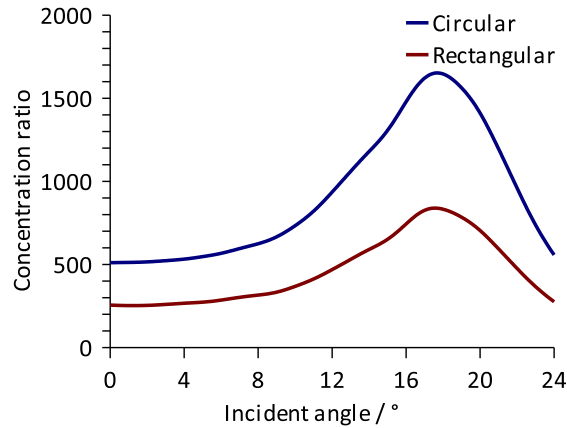


Figure 4. Concentration ratio against incident angle for identical laterally moving lenses setups except their circular (upper) and squared (lower) entrance apertures and receivers, respectively

By changing from a circular to a squared entrance aperture, the concentration performance over the entire aperture angle drops considerably (approximately by a factor of 2). This decrease in performance is well-known and it is characteristic for cutting out rectangular (squared) regions out of rotational symmetric circular lenses. In addition, further losses result from the fact that utilized high-efficient solar cells normally have a squared aspect ratio. Or, to put it in other words, the rotational symmetric lens design is clearly mismatching the overall symmetry of this given optical design problem. Namely that all incident directional vectors lie in a plane (from now on in x-z plane). Without knowing anything about the optimal lens shapes it is evident that the symmetry of the lens surfaces should reflect the overall symmetry of the given problem statement.

\*By courtesy of Prof. Dr. Udo Rohlfing, Hochschule Darmstadt, Germany

## 4. BREAKING THE ROTATIONAL SYMMETRY

The rotational symmetric lenses in Section 3 showed promising performance properties as tracking-integrated CPV optics if analyzed individually. However, by changing the entrance aperture from circular to square shape to obtain lens array structures with a high fill factor, the concentration performance drops considerably. In the following, an extended three dimensional design algorithm is presented which will help to overcome this drawback.

### 4.1 Extended SMS3D algorithm to design laterally moving optics

The capabilities of the SMS3D design algorithm and its wide range of possible applications were presented in various publications.<sup>6, 12, 13</sup> The objective is to extend the existing SMS3D design algorithm in order to obtain relatively moving *free form* optics. This extended design algorithm consists of three basic steps which are shown in Figure 5(a)-(c).

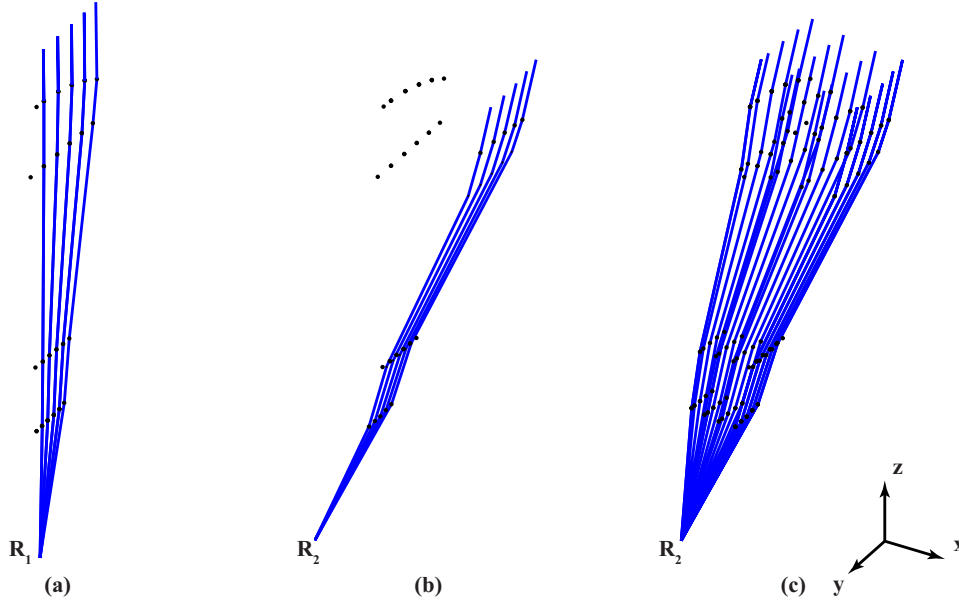


Figure 5. Shown are three basic steps of an extended SMS3D design procedure for laterally moving optics

The desired field of view (FOV) is defined by the incident directional vectors (pointing at the sun) within  $\pm 24^\circ$  lying in the x-z plane. Due to the overall symmetry of this optical design problem it is evident that the final lens will also have a 2-fold discrete rotational symmetry ( $C_2$ ). Thus it is only required to design one quadrant of each lens. The full lenses can then be constructed through multiple mirroring steps.

The first design step is illustrated in Figure 5(a). The design process starts with a SMS2D design in the orthogonal y-z plane for two auxiliary incident directions having opposite signs. The parameters describing this auxiliary construction can be later on optimized. As result two initial SMS2D seed curves for both plano-convex lenses are obtained in one symmetry plane.

Figure 5(b) illustrates the next step where the second lens is now shifted by a certain offset in negative x-direction. By choosing a specific design angle  $\pm\theta$  in the x-z plane, a correspondent receiver point  $R_2$  and an optical path length, it is possible to launch rays coming from  $R_2$ , refract them at the 2D seed curve on the lower surface and calculate a first 3D rib on the upper surface.

With these two curves on the upper surface it is possible to patch a polynomial surface which contains both curves. Figure 5(c) shows a calculated grid of points on the surface patch and rays passing through. The fixed optical path length is then used to obtain points on the final surface of the lower lens by refracting all rays towards  $R_2$ . These three steps allow to calculate the first surface patch. The final steps then include further alternating SMS design for  $\pm\theta$  and a final mirroring process to obtain the complete plano-convex lenses.

## 4.2 First ray tracing results

Analog to Section 3, the new design algorithm is now used to redesign the optical system for monochromatic light, a half aperture angle of  $24^\circ$  and an angular acceptance  $\pm 0.28^\circ$  (polar axis tracker alignment). Furthermore, the overall system dimensions are chosen to match the previously discussed rotational symmetric design. The final result for a design angle  $\theta = 19^\circ$  was obtained by rudimentary optimization of various design parameters using a constraint optimization (based on MATLAB's *fminsearch* function). As a last step, a rectangular entrance aperture is chosen which maximizes the surface area of the entrance aperture and thus the concentration ratio. Its aspect ratio is approximately 1.4 for x- to y-direction. Figure 6 shows this final non-rotational symmetric design suitable for the application in lens array structures.

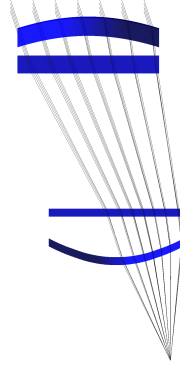


Figure 6. 2-fold rotational symmetric laterally moving lenses at design angle  $19^\circ$  and for rectangular lens apertures

The concentration performance of the new system design is again evaluated using the ray tracing analysis described in Section 3. Analog to Figure 4, Figure 7 shows the concentration ratio against the incident angle from  $0^\circ$  to  $24^\circ$  for the rotational symmetric and non-rotational symmetric design (rectangular lens and receiver apertures), respectively.

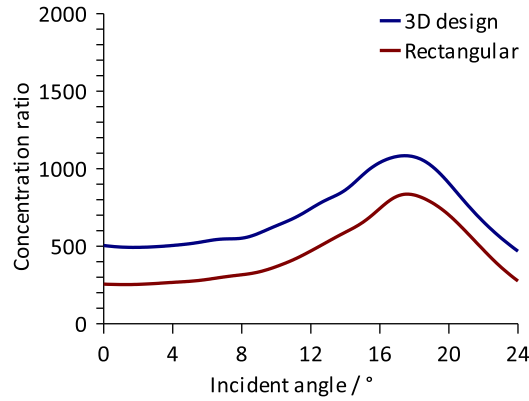


Figure 7. Concentration ratio against incident angle for 2-fold rotational symmetric 3D design (upper curve) and rotational symmetric design (lower curve), both having rectangular lens and receiver apertures.

The non-rotational symmetric lens design achieves again about  $500\times$  concentration over the entire angular range of  $\pm 24^\circ$ , this time however fully suitable for application in lens array structures. This quantitative evaluation prove the benefits originating from a non-rotational symmetric lens design for one-dimensional tracking integration in concentrating photovoltaics. Further desired attributes of CPV systems are the uniformity of flux, color mixing on the solar cells surface and an increased acceptance angle which is directly related to misalignment tolerance. A well accepted solution to achieve this is a final stage concentrator on top of the solar cell. Further work should also cover the use of this component in helping to increase the aperture angle, ensure color mixing and increase the acceptance tolerances.

## 5. CONCLUSIONS

Within the scope of this work, the general concept of integrating tracking in concentrating photovoltaics was briefly summarized and possible fields of application were classified. The main objective was to verify and compare the suitability of rotational and non-rotational symmetric laterally moving lens designs for their application in lens array structures. The rotational symmetric optical system showed a considerable drop in performance when considering rectangular lens and detector apertures. The fundamental link between the symmetry of the optical design problem and the correspondent lens design led to an extended SMS3D algorithm, capable of designing non-rotational symmetric laterally moving lenses. The resulting lens design achieved about  $500\times$  concentration over the entire angular range  $\pm 24^\circ$ , being fully suitable for application in lens array structures.

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